Ecosystems (2004) 7: 563–572
DOI: 10.1007/s10021-004-0234-4

ECOSYSTEMS

ORIGINAL ARTICLES

Land-use Related Changes in Aboveground Carbon Stocks of Austria's Terrestrial Ecosystems

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ABSTRACT

Land-use changes considerably alter the patterns and processes of terrestrial ecosystems. In an attempt to assess the impact of the human domination of ecosystems, this study quantifies the effect of human activities on aboveground carbon stocks in vegetation, based on a comparison of potential and actual vegetation in Austria. Following an accounting approach, statistical and GIS data on vegetation, elevation, land use, biomass harvest, as well as forest inventories and real estate statistics, were entered into the assessment, which was performed at the level of municipalities ($n = 2{,}350$). The results show that aboveground carbon storage in Austria has been considerably reduced by human activities. Actual vegetation contains 64% less carbon than would be expected in potential vegetation. The conversion of forests to cropland, grasslands, and urban areas has contributed 77% to this reduction in carbon stocks, the remaining 23% is due to forest management. In Austria, aboveground carbon stocks in forests have been reduced by 30% due to reductions in stand age and changes in forest species composition. Placing the data in a historical context, this analysis suggests that the current terrestrial carbon sink is a reversal of past carbon losses.

Key words: standing crop; aboveground carbon stock; terrestrial carbon sinks; human domination of ecosystems; Kyoto protocol; environmental history.

INTRODUCTION

Changes in land use and land cover result in pervasive alterations in the patterns and processes of terrestrial ecosystems and are thus a major driver of global environmental change. In an attempt to quantify the effects of human domination of Earth's ecosystems (Vitousek and others 1997), ecologists have assessed the human appropriation of net primary production (HANPP) (Vitousek and others 1986; Wright 1990; Haberl 1997; Haberl and others 2001). HANPP quantifies land use–induced changes in yearly fluxes of biomass and thus in the amount of trophic energy available each year to heterotrophic organisms in terrestrial ecosystems (Wright 1990; Haberl 1997; Haberl and others 2002). In using the land, however, humans not only alter yearly fluxes of materials and energy through ecosystems, they also change the ecosystem's biomass stocks (Houghton and others 1983; Houghton 1995; Schimel 1995).

It is generally recognized that terrestrial ecosystems play an important role in the global carbon cycle. Carbon is retained in live biomass, in decomposing organic matter, and in soil, and it is exchanged naturally between these pools and the atmosphere through photosynthesis, respiration, decomposition, and biomass burning. Terrestrial

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Received 9 September 2002; accepted 18 June 2003; published online 28 May 2004.

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ecosystems act as carbon sinks if net primary productivity (NPP) exceeds heterotrophic respiration and losses due to disturbances (that is, when net biome productivity [NBP] is positive), resulting in a buildup of carbon stocks, and represent a carbon source if NBP is negative and a decrease in carbon stocks takes place. Human activities affect these fluxes between the different carbon pools, either directly or indirectly, inducing changes in the size of the different carbon pools and thus altering the biogeochemical cycle of carbon. These land-use–related changes in the carbon cycle are occurring at an increasing rate around the globe, with remarkable regional variations, especially between industrialized and developing countries.

Such changes in biomass stocks in ecosystems, associated with a net flux of carbon between the atmosphere and biota, are highly relevant for current policies that aim at slowing down carbon accumulation in the atmosphere (Watson and others 2000). Due to their partial integration in the Kyoto protocol, land-use–related carbon sources and sinks have gained much scientific and even political attention in recent years. Because many of these ecological carbon flows are highly uncertain and difficult to measure, it is common to assess net fluxes between biota and atmosphere by calculating differences in carbon stocks at different points in time, because it is possible to evaluate these values with higher precision than is the case for many yearly flows. Changes in the size of the different carbon pools represent the aggregated effects of human activities on natural carbon flows.

In an attempt to quantify the overall effect of land use on the amount of carbon stored in live vegetation, this paper assesses land use–related changes in terrestrial carbon stocks by comparing the patterns of the actually prevailing ecosystems (that is, properties of current vegetation) with those one would expect to find in the absence of human activities (that is, properties of potential vegetation) (Tüxen 1956). Such a comparison can be used as a means of assessing the physical scale of human activities in contrast to natural patterns and processes—in other words, as a means of quantifying the "human domination of ecosystems" (Vitousek and others 1997). Because potential vegetation patterns are an approximation of pre-anthropogenic vegetation patterns, this approach addresses the environmental history of the human–nature interrelationship and is furthermore suitable for exploring the underlying mechanisms of recent patterns of terrestrial carbon flows such as, for example, the current role of mid- and high-latitude vegetation as a sink for atmospheric carbon.

In this, I adapt the approach proposed by Vitousek and others (1986), Wright (1990), and Haberl (1997) for assessing human alterations of ecological energy flows. Instead of focusing on flows (the flow of energy through ecosystems), I will apply their concept to the assessment of human alterations of stocks—that is, the stock of carbon stored in living vegetation.

The example used in this paper is Austria, a highly industrialized Central European country with medium population density (area, 83,000 km^2; current population, 8 million). Owing to Austria's mountainous landscape, forests cover more than 45% of its land area, a rather high percentage by Central European standards (EU average, 40%).

MATERIALS AND METHODS

The aim of this study was to quantify and analyze the impact of human activities on ecosystems, not to elaborate a predictive model of future human effects on the carbon stored in ecosystems. Thus, instead of a formal model, a flexible approach was used that allows a variety of data on land use and ecosystem properties to be incorporated. These data include, for example, agricultural statistics, forestry statistics and inventories, land-use statistics, and other data on land use and land cover in Austria. All calculations were performed using a database with high spatial resolution that has municipalities (n = 2,350) as its smallest unit. In general, an "accounting approach" was used; the carbon stored in both potential and actual vegetation was calculated by (a) segmentation of the area into units assumed to be homogenous with respect to carbon stocks per unit area and (b) assessment of typical (characteristic) values for carbon stocks for each of these spatial units.

The focus of the study is on changes in the aboveground standing crop of biomass. Other biospheric carbon pools—such as belowground biomass, litter, dead wood, soil carbon, and carbon stored in human artifacts (that is, carbon in buildings and products)—will not be treated. The standing crop is correlated with the carbon content of ecosystems, because carbon may be assumed to make up 42%–55% of dry-matter biomass (Körner and others 1993; Schulze 2000). In other words, standing crop represents a stock of organic matter in ecosystems—in contrast to the flux represented by NPP or net ecosystem production. As a result of the International Biological Programme (IBP), reliable data exist for the aboveground standing crop of several vegetation units such as forests, grasslands, swamps, marshes, and so on. However, data on the

Figure 1. Elevation map and ecoregions of Austria, as used in the calculations. Sources: Mayer (1974), Wagner (1984), and ÖSTAT–FBVA (1995) (as modified).

belowground standing crop, especially in agricultural areas, are still rather uncertain, because the belowground standing crop is seasonally highly variable and difficult to measure (Waring and Schlesinger 1985; Vogt and others 1986; Singh and others 1984; WBGU 1998). Owing to such uncertainties and the lack of reliable data compilations, this study is restricted to aboveground standing crop. Metric tons of dry matter are used as the basic unit. In converting dry matter to carbon, a conversion factor of 0.45 was used (Körner and others 1993; Houghton and others 1983).

Potential Vegetation

The standing crop of potential vegetation was assessed on the basis of vegetation data and a GIS elevation model. For the establishment of "homogenous" area units, Austria's territory was divided into four ecological regions (ecoregions), on the basis of analyses of potential vegetation maps (Wagner 1984; Mayer 1974; ÖSTAT–FBVA 1995) (Figure 1). All Austrian municipalities were then assigned to an ecoregion. These regions represent territorial units that are relatively homogenous with respect to climate, soil characteristics, intergradation of the altitudinal vegetation belts, and sequence of dominant plant associations according to the latter. A further division, as established in vegetation ecology, for instance, was found to generate higher variation within the ecoregions than among them according to the parameter of interest. These ecoregions, three of which are alpine and one of which is within the plain territory surrounding the Alps, are (a) the central alpine zone, (b) the intermediate alpine zone, (c) the alpine margin, and (d) the pre-alpine regions. For each of these regions, an individual sequence of the altitudinal vegetation belts was established on the basis of data from the literature (Mayer 1974; Ozenda 1988), resulting in 10 zones (Table 1) bearing distinct climax associations—namely, old-growth forests as well as alpine shrubs and tundra above the timber line. Only zonal vegetation was considered, because azonal vegetation units (such as natural grasslands) play no significant role with regard to area extent (Wagner 1984). The standing crop for vegetation on rocky ground and glaciers (above 2,800 m) is assumed to be negligible (Table 1).

The appraisal of standing crop values for the potential vegetation's different climax forests was based on IBP research data (Cannell 1982) and recent Austrian investigations (for details, see Erb 1999). Because the IBP data include data for forests of all ages, the persistent biomass stocks of old stands was assessed using logistic regressions for the standing crop of the respective climax associations depending on stand age. Austria's climax forest associations have been identified as follows (named by dominant species): oak (*Quercus* spp.), spruce (*Picea abies*), fir (*Abies alba*), pine (*Pinus* spp.), and other decidous forests (mainly alluvial forest associations). A logistic equation was used for the regression (Ricklefs 1990): 1

$$SC(t) = K/(1 + b \cdot e^{-r \cdot t})$$

where SC denotes standing crop; t, stand age; K, the maximum persistent standing crop of old-growth stands of the respective species; b, a regression factor; and r, a growth factor. For example, Figure 2 shows the regression performed for forests dominated by beech (*Fagus sylvatica*), using a least squares fit approach. These regressions yielded relatively satisfactory fits ($0.54 < r_2 < 0.83$, depending on the forest associations), whereas regressions between standing crop, temperature, and precipitation failed to produce satisfactory results. The standing crop for alpine communities, mainly alpine tundra, were assessed on the basis of literature data (Ajtay and others 1979; Franz 1979; Paulsen 1995); for more details, see Erb (1999).

Table 1 shows the standing-crop estimates of the different potential vegetation units according to the altitudinal vegetation belts and the four ecoregions, as used in the calculations. Reductions in potential standing crop due to natural disturbances were not explicitly considered due to the lack of data. Stand-destroying fires can be assumed to play a minor role because of Austria's humid climate. The standing crop of frequently disturbed areas, such as the subalpine zone, was estimated using mixed values for pioneer (grasslands) and mature associations (subalpine forests), thus implicitly taking the effects of natural disturbances into account.

Table 1. Standing Crop of Typical Vegetation Units of Potential Vegetation in Austria

	Colline Zone (0–600 m)	Montane Zone (600–1400 m)	Lower Subalpine Zone (1,400–1,800 m)	Higher Subalpine Zone (1,800–2,200 m)	Alpine Zone (2,200–2,800 m)
Central Alpine zone	Oak (290 t/ha)	Spruce (285 t/ha)	Spruce (184 t/ha)	Larch–pine (127 t/ha)	Alpine tundra (10 t/ha)
Intermediate Alpine zone	Oak (290 t/ha)	Spruce–fir (361 t/ha)	Spruce (184 t/ha)	Larch–pine, alpine tundra (88 t/ha)	Alpine tundra (10 t/ha)
Alpine margin	Oak–beech (297 t/ha)	Spruce–fir–beech (342 t/ha)	Spruce–fir, bush land (146 t/ha)	Alpine tundra (10 t/ha)	Alpine tundra (10 t/ha)
Pre-Alpine regions	Oak–beech (297 t/ha)	Spruce–fir–beech (342 t/ha)	No vegetation	No vegetation	No vegetation

All values are dry matter biomass.

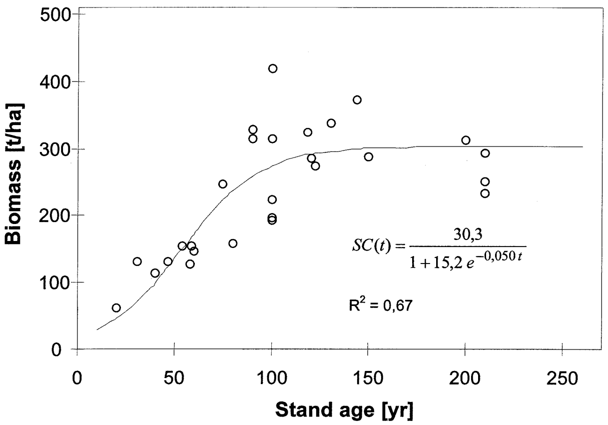

Figure 2. Logistic regression for the standing crop of Austria's beech forest, depending on stand age, as an example for the analysis of the IBP data set (Cannell 1982) and Austrian primary data by application of logistic regressions. The regression, applying the formula Standing Crop = SC (t) = K/(1 + b.e$^{-r.t}$), results in a K (= maximum persistent standing crop of old-growth stands) of 30.3 kg/m^2 dry matter. Only study sites with a mean annual precipitation of more than 450 mm and a mean annual temperature between 4°C and 14°C were included. Sources: Cannell (1982), Walter and Lieth (1973), Erb (1999).

Actual Vegetation

In assessing the actual standing-crop inventory, the land-use data set of the Austrian Central Statistical Office was used (ÖSTAT 1992, ÖSTAT 1995). The data refer to municipalities as the smallest spatial unit. This spatial resolution was also used in establishing the data set for potential vegetation and allows the discrimination of approximately 40 categories of land use, comprising finely differentiated agricultural and grassland units. Further data consider built-up areas, gardens, alpine pastures, and so on. The minimum area recorded in these land-use statistics is 1 ha (10^4 m^2). In real estate statistics, which were used to assess built-up land and other urban areas, there is no such lower limit. There is some spatial distortion due to the fact that a parcel of land is allocated to the municipality where the owner of the parcel resides, even if the parcel itself is located in another municipality (ÖSTAT 1992; Schieler and others 1996; Gerhold 1992). To minimize such distortions, elevation data were additionally used to provide for adequate allocation of vegetation units within the municipalities. For reasons of data availability and completeness of the data set, the actual standing crop was assessed using data for the year 1990.

The standing crop of the actual vegetation was appraised by assessing characteristic values for the different land-cover units mentioned above. Special attention was paid to forests because they represent by far the largest component of the total standing crop. The aboveground standing crop of actual forests was estimated with two independent methods: (a) The logistic regressions derived from the analysis of the IBP data (see above) were applied to data on age-class distribution and forest area for the different forest types, derived from the forest inventory (Schieler and others 1996); and (b) the standing crop of Austrian forests was calculated on the basis of data for standing timber from the forest inventory. Because the forest inventory contains only data on bole wood including bark, "expansion factors" based on data from the literature (Cannell 1982; Burschel and others 1993; Körner and others

1993) were used to obtain estimates for total aboveground standing crop. These expansion factors, reflecting branches and twigs, leaves, fruit, blossoms, and understory, have been developed independently for seven different stand age classes (Mitscherlich 1975; Paulsen 1995). Vegetation gaps, clear-cut areas, and bush areas were also considered (Dörflinger and others 1994; Sattler 1990). The results of the two approaches on the national level differed by only 5%. Because the first method does not allow for regionalization to the level of municipalities, only the results from method (b) were considered further.

The standing crop of agricultural areas was assessed as the peak biomass of fields—in other words, the standing biomass at the time of harvest. It was calculated by appraising agricultural harvest from harvest statistics (ÖSTAT 1992) and applying "harvest indices" (Krausmann 2001) to obtain peak standing crop.

The standing crop of most grassland types was estimated on the basis of a broad literature review because correlations of harvested biomass and standing crop by harvest indices produce flawed results due to the range of annual harvest frequency (one to three harvest events during one vegetation period, depending on the intensity of grassland use). The literature review resulted in the following values: 0.25 kg C/m^2 for pastures and meadows, 0.17 kg C/m^2 for fallow areas, and 0.19 kg C/m^2 for alpine pastures above 1,700 m elevation (for details, see Erb 1999).

The standing crop of alpine shrubs was assumed to be equal to that of the potential vegetation (0.45 kg C/m^2 dry matter), whereas no vegetation was assumed to prevail in built-up areas.

RESULTS

The total aboveground standing crop of the potential vegetation—assumed to consist of old-growth forests and alpine tundra—is estimated at 994 million metric tons of carbon (or 2,209 Mt dry matter). Forests account for the bulk of this biomass (99.8%). Deciduous forests dominate with 45.5%, coniferous forests account for 26.7% of the total biomass, and mixed forests account for 27.7%.

The standing crop of actual vegetation in Austria is significantly smaller than that of the potential vegetation (Figure 3). The current aboveground standing crop is about 360 million metric tons of carbon (802 Mt dry matter), which is 64% less than the corresponding value for the potential vegetation. Forests still predominate, accounting for 96.0% of the total actual standing crop. Forest management, however, resulted in a massive change in the predominant forest types: coniferous forests dominate with 55.5%, mixed forests contribute a further amount of 38.9%, whereas deciduous forests—the predominant forest type of the potential vegetation—contribute only 5.6% to the carbon stocks of forests. As for the other categories, agricultural areas contribute 1.5%, grasslands contribute 1.0%, and all other categories contribute 1.5% to the overall carbon stocks in Austria's current aboveground vegetation.

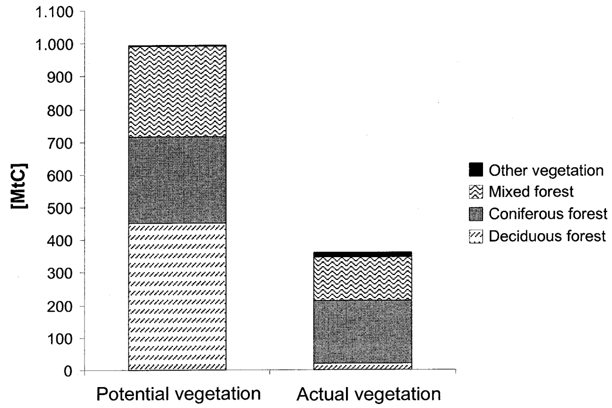

Figure 3. Carbon stocks of the potential and actual vegetation of Austria. "Other vegetation" is the sum of agricultural land, grassland, alpine tundra, and land used for horticulture.

Figure 4 shows the aboveground standing-crop results for potential and actual vegetation aggregated to the level of municipalities. The potential aboveground standing crop does not follow a continuous gradient from low to high altitudes but is highest at medium altitudes (Table 1). Deciduous tree species dominate at low elevations in the prealpine regions (for example, *Fagus sylvatica, Quercus* spp.) and reach considerably lower standing crop maxima than do firs (*Abies alba*). Firs play an important role in the potential vegetation of alpine forest communities, particularly in the montane vegetation belt (600–1,400 m elevation) of the intermediate alpine zone and the alpine margin. Thus, although lowlands generally fall between 13 and 14 kg C/m^2, the aboveground standing crop exceeds 15 kg C/m^2 in peripheral alpine regions. The standing-crop. values are much lower in the central alpine zone, where high alpine forests and alpine tundra above the timberline are dominant. Note that the carbon stocks shown in Figure 4 represent average carbon stocks of whole municipalities and were derived considering the prevailing mixture of the different land-use classes.

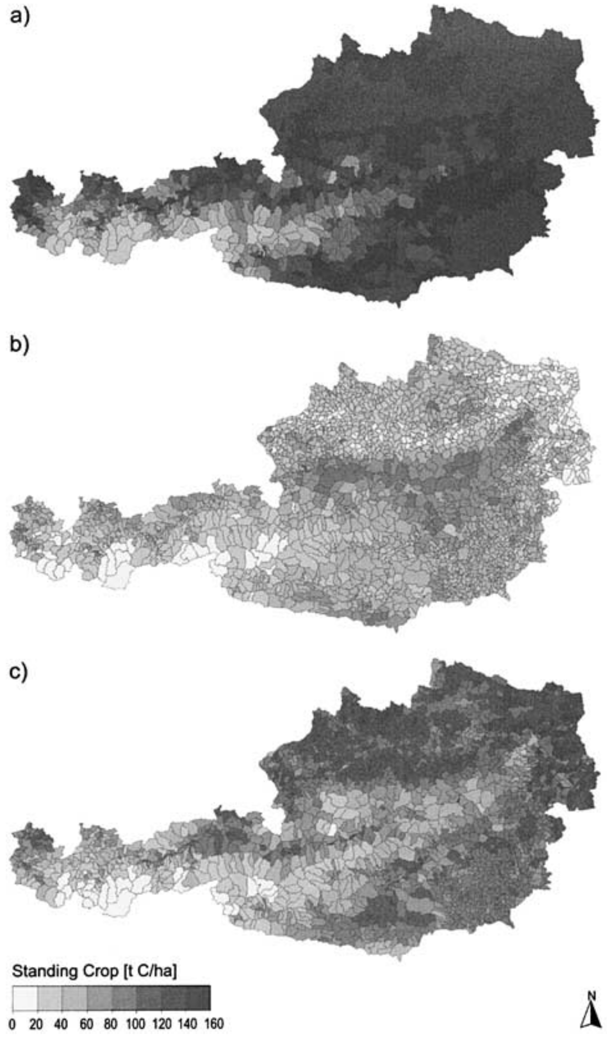

Figure 4. Aboveground carbon stocks in terrestrial vegetation in Austria on the level of municipalities. (**a**) Carbon stocks of the potential vegetation. (**b**) Aboveground carbon stocks of actual vegetation. (**c**) Reduction of the aboveground carbon stocks as the difference between "a" and "b".

The amount of carbon stored in current aboveground vegetation is significantly lower than that which would be stored in the potential vegetation; this is mainly due to the modification of pristine forests to make way for agricultural land and clearings for urban areas. Areas in the peripheral alpine regions are still dominated by forests and hence show relatively high levels of carbon stocks, whereas the central alpine zone reaches low levels similar to those prevailing in the pre-alpine regions. This is mainly due to the high percentage of subalpine and alpine vegetation in the central alpine zone. Nevertheless, as Figure 4c reveals, the central alpine zone has experienced the least reduction in standing crop, whereas the carbon stocks of the pre-alpine regions have been considerably reduced. The highest reduction levels are found in the eastern parts of Austria, where the most intensively used croplands are concentrated, and as shown in Figure 4c, in Austria's broad alpine valleys and basins, which are suitable for agricultural intensification. An almost 100% reduction is found in municipalities dominated by urban areas.

On a national level, due to various human activities, only 36% of the aboveground standing crop of the potential vegetation remains in Austria's terrestrial ecosystems. As Table 2 indicates, this reduction of 633 Mt C in standing crop is due mainly to modifications of pristine ecosystems—namely, the historic clearing of forests for agricultural purposes as well as settlement activities such as the building of infrastructure. Taken together, these activities contribute 77% to the overall standing-crop reduction. Forest management, which primarily affects stand age and species composition, contributes the remaining 23% to the anthropogenic reduction of Austria's aboveground terrestrial carbon stock.

Table 3 compares the actual standing crop of main vegetation classes currently prevailing in Austria with the standing crop of the potential vegetation that would be expected to grow on the corresponding area. Whereas the aboveground carbon stock of the potential vegetation reaches 12 kg C/m^2 on average and ranges from 0.5 (alpine tundra) to 14.5 kg C/m^2 (climax forests on agricultural areas), the aboveground carbon stock of the actual vegetation is only 4.4 kg C/m^2, with values of 8–10 kg C/m^2 in forests, 2 kg C/m^2 in horticulture, and less than 0.5 kg C/m^2 in agricultural areas. Depending on land-cover class, between 0% and 77% of the initially existing standing crop remains. The percentage of remaining standing crop is highest in forests (70% on average) and lowest in agricultural areas, grasslands, and built-up areas (0–3%). The reduction in standing crop due to forest management ranges from 23% in coniferous forest to 38% in mixed forests. The reduction in standing crop is highest in mixed coniferous/deciduous stands because of human-induced changes in species composition, marked by a significant reduction in the density of firs (*Abies alba*). For alpine tundra, the actual vegetation was assumed to bear 100% of the potential standing crop per area unit. However, alpine land use extends the alpine tundra because over time with changing use patterns it results in a general lowering of the timberline (Ellenberg 1996). Hence, the extension of alpine tundra contributes 0.5% to the overall reduction in aboveground carbon stocks (Table 2).

Table 2. Shares of Different Land-use Types in Overall Reduction of Standing Crop by Actual Land Cover

	Potential Vegetation	Actual Vegetation (Mt C)	Reduction in Carbon Stock	Share of Overall Reduction (%)
Forest	493	347	147	23.2
Agriculture	194	5	189	29.8
Grassland	222	4	218	34.4
Horticulture	14	2	12	1.9
Alpine pasture	31	1	30	4.8
Alpine tundra	6	3	3	0.5
Built-up area	34	—	34	5.4
Total	994	361	633	100.0

Rounded values

Table 3. Carbon Content of Potential and Actual Vegetation in Austria by Actual Land cover Type

	Area (km^2)	Potential Vegetation (t C/ha)	Actual Vegetation (t C/ha)	Remaining Portion (%)
Coniferous forest	23,669	105	81	77
Deciduous forest	2,080	134	93	70
Mixed forest	14,040	154	96	62
Forest total	39,789	124	87	70
Alpine tundra	5,607	5	5	100
Agriculture	13,384	145	4	3
Grassland	15,288	145	2	2
Alpine pasture	4,584	68	2	3
Horticulture	969	145	21	15
Built-up area	2,349	145	—	0
Austria total	83,859	120	44	36

Rounded values.

DISCUSSION

The impact of human activities on aboveground carbon stocks in Austria's vegetation has been substantial. According to this study, current land-use patterns have led to a reduction of the aboveground standing crop in Austria by 630 Mt C, which is 64% of the carbon hypothetically retained in the potential vegetation. The main cause of the reduction in aboveground carbon stocks is the conversion of pristine ecosystems (mainly forests) many centuries ago to managed ecosystems, such as agricultural areas and grasslands. In addition to ecosystem conversion, the management of forests substantially contributes to the reduction of aboveground carbon stocks. Although forest management in Austria can be assumed to follow a "sustainability rule" (that is, the forest harvest must be less than the timber increment), the effect on carbon storage is nevertheless significant. Management practices such as selecting fast-growing tree species and harvesting old-growth stems reduce forest stand age, which eventually results in carbon stock declines, even when long-term site productivity is not affected (Harmon and others 1990). However, reduction ratios of more than 50%, as calculated by Harmon and others (1990) and Cooper (1983) on the basis of a site-specific model and maximum sustained yield assumptions, respectively, have not been reached in Austria.

According to the findings of this study, the reduction in aboveground standing crop in forests ranges from 23% to 38%, depending on forest type. This may be due to the extensive forest management practiced in Austria for at least several decades, with harvest ratios substantially below the maximum sustained yield. As the Austrian Forest Inventories show (Schieler and others 1996; Büchsenmeister and others 1999; Weiss and others 2000), the average harvest ratio was only about 70% of the timber increment from 1961 to 1996, which resulted in a significant buildup of standing crop in forests. Furthermore, 12% of Austria's forested areas are nonmanaged stands in alpine regions (that is, protective forest stands), a relatively high proportion compared to other European countries. Therefore, the reduction in Austria's aboveground carbon stocks may be lower than that of other European countries. It needs be mentioned, however, that wood products and biomass fuels derived from harvested wood can reduce the demand for fossil fuels and thus contribute to a lowering of carbon emissions. A consideration of these effects, which could eventually counterbalance the reduction in ecological carbon stocks (Matthews 1996; Marland and Schlamadinger 2002), was beyond the scope of this study.

Currently, the vegetation of the global temperate and boreal zones acts as a net sink for atmospheric carbon, mainly due to an increase in carbon stocks in forests (Kauppi and others 1992; Sedjo 1992; Schimel and others 2001). Austria's forests have also grown with respect to area and biomass per unit area over the course of the last several decades, resulting in a significant buildup of carbon stocks in phytomass (Jonas 1997; Weiss and others 2000). However, a comparison of the carbon retained in the potential and actual vegetation reveals that the recent role of vegetation as a sink for atmospheric carbon probably represents—mostly or entirely—a recovery from past carbon losses.

One underlying mechanism for the vegetation's current function as a carbon sink can be identified by examining the history of the human–nature interrelationship. Before the Industrial Revolution, society's needs for materials and energy were met almost entirely by biomass. Because little energy was available for increasing agroecosystem productivity, socioeconomic pressure on terrestrial ecosystems was considerable (Sieferle 2001; Smil 1991; Krausmann 2001). Humans extended cultivated areas even to relatively unfavorable sites and used forest ecosystems intensively for firewood and for litter extraction and grazing. As a consequence of this exhaustive use, little biomass remained in the ecosystems. But the situation changed as fossil fuels became available and the Industrial Revolution began. As an area-independent energy source, fossil fuels allowed for supplementary energy input and fertilizer application, resulting in an increase in yields per unit area on cultivated lands. Consequently, a higher output could be achieved on small areas, triggering an economic optimization process in the agricultural production system. As agricultural production tended to be concentrated on favorable sites and areas with marginal economic gains began to be abandoned, reforestation occurred. Furthermore, the availability of fossil fuels decreased the demand for firewood, which led to a reduction of wood harvest.

A recent analysis of historic land use in Austria by Krausmann (2001) shows that the extent of agricultural areas has decreased in favor of forested areas over the last century. Forest area has expanded by 23% since 1830, and the human appropriation of NPP declined from 60% to approximately 50% in the same period (Krausmann 2001). These data on historic land use in Austria suggest that there must have been a minimum of carbon stock in the vegetation that probably occurred some 200 years ago. Besides changes in abiotic conditions (for example, carbon dioxide fertilizing effect, temperature changes), which could be of minor importance (Schimel and others 2001; Caspersen and others 2000), one explanation for the current role of vegetation as a carbon sink is that the increasing use of fossil fuels induced a partial reversal of the past of depletions of terrestrial carbon stocks.

These conclusions raise serious questions as to the usefulness of policies that would grant carbon credits for carbon sinks related to land-use change in the time frame between 1990 and the commitment period, as proposed by the conference of the parties (COP) in the 1997 Kyoto protocol. In addition to issues of verfication and validation and questions related to the permanence of these sinks (compare Watson and others 2000) of these sinks, the mechanisms responsible for the currently observed carbon sinks sorely need to be addressed. Because the fossil fuel–based energy system is itself a contributing factor to the land-use changes that resulted in the current carbon sinks, enacting a policy that would allow industrialized countries to emit more greenhouse gases from fossil fuel combustion in return for changes in land cover that could serve to per petuate or intensify these ongoing trends. Political measures which take these trade-offs between fossil energy use and terrestrial sinks into account—will be essential for realizing improvements to the overall carbon budget.

ACKNOWLEDGMENTS

This paper draws on research conducted in the Kulturlandschaftsforschung (Cultural Landscapes Research) research program, funded by the Austrian Federal Ministry of Education, Science, and Culture. The study is part of the Land-Use and Land-Cover Change (LUCC)-endorsed project no. 33, "Land-use Change and Socioeconomic Metabolism: A Long-term Perspective." My thanks go to Helmut Haberl, Fridolin Krausmann, and two anonymous reviewers for their valuable comments on this paper and to Antje Lewis for correcting the English.

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